

DESCRIPTION AND IMPLEMENTATION OF A METHOD  
FOR CHARACTERIZING NOISE SOURCES IN JETS

J. Taillet

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| 16. Abstract<br><br>Description of a technique for characterizing noise sources in jets which is based on the measurement of infrared emission. The proposed method is an extension of Lighthill's theory and takes as the initial variables the mean parameters and the moments derived from experimentally obtained fluctuating parameters, which are introduced into a computer program yielding the spectrum and the radiation pattern of the sonic far field. The acoustic variables can thus be calculated from the measured characteristics of the jet turbulence, so that the problem of noise reduction is reduced to an aerodynamics problem. |                                                      |                                                            |                     |
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DESCRIPTION AND IMPLEMENTATION OF A METHOD  
FOR CHARACTERIZING NOISE SOURCES IN JETSJ. Taillet<sup>†</sup>I. INTRODUCTION

/1\*

The search for means of reducing jet noise coming from the nozzles demands thorough knowledge of the physical mechanisms that engender this noise.

The present article describes and discusses a method utilized by the O.N.E.R.A. National Bureau for Aerospace Studies and Research in cooperation with SNECMA National Company for Design and Manufacture of Aircraft Engines, under the auspices of the Aeronautics Technology Department and the General Secretariat for Civil Aviation, characterizing noise sources and predicting the acoustical pattern of hot jets by use of reduced-scale models of nozzles designed for engines presently on SNECMA drawing boards.

The fundamentals of jet noise theory were worked out by Lighthill, starting in 1952 1, 2, 3. This author shows that the acoustic quantities pertaining to the jet may be deduced from flow turbulence characteristics. The point of departure of his theory is a relation, deduced from general fluid mechanics equations, between the second order partial derivatives and the density analogous to the sound propagation equation with respect to the first member. The second member of this equation is a source term characterizing the turbulent exhaust medium. A second

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\*Numbers in right hand margin indicate pagination in foreign text.

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relation may be deduced from the first. This is an integral relation to the Green function type, enabling the density at an observation point to be expressed as a function of source terms for the entire turbulent medium. Integration is simplified for sufficient distances from the source, which should in principle lead to determination of the sound intensity, the spectral density, and the radiation pattern in the far field, by development and use of a digital computer program. In actual fact, the complexity of the source terms is such that no author has attempted such direct usage. Two theoretical approaches have thus far enabled fruitful use to be made of the properties expounded by Lighthill.

The first approach, worked out by Lighthill himself, then by Ribner 4, 5, Ffowcs-Williams 6, and Lilley 7, to quote only a few, consists of using the physical model of aerodynamic noise sources and deducing, from the physical properties of this model, a number of dimensional relations. It is possible to make an approximate prediction of the evolution of the jet's acoustic pattern as a function of the mean flow parameters.

This line of research has proved extraordinarily fruitful. The results of dimensional analysis take good account of the experimental results on sound power, the radiation pattern, and the spectral noise distributions, for the subsonic and supercritical 72 fields. By a judicious choice of simplifying hypotheses, account may be taken of the separate effects of convection, the aircraft speed, and reflection, or these effects may be accounted for simultaneously if we complicate the model. However, this method does not furnish the absolute value of acoustic quantities; it gives no information of the influence of structural modifications imposed on the jet by a change in nozzle shape, or the presence of a silencer; finally it is not sufficiently detailed to predict the

consequence of a spacewise evolution of the turbulence parameters along the flow.

A second approach consists of confining the problem to a particularly simple case to further analytical calculation of Green's function, using the remarkable simplifications introduced by this choice. This is the path followed by Proudman, who dealt with the problem of noise emitted by homogeneous and isotropic turbulence [8] and deduced expressions for the sound power and the spectral density, the absolute values of which are thus known. It must be noted, however, that this method is applicable only to turbulence in the mixing zone of jets; it is thus of limited usefulness in the problem occupying us here.

Bearing in mind the limitations of the two above approaches, it is tempting to seek for results which, in practical scope, go beyond the results of dimensional analyses by using a simplified computer program, based on a theory of Lighthill, and using as input quantities the mean parameters and moments deduced from fluctuating parameters supplied by experiment. Such a method would have the advantage of enabling us to calculate acoustic quantities from the measured jet turbulence characteristics, thus converting the noise reduction problem into one of aerodynamics, and modifying this turbulence by appropriate devices.

To implement this new method, we must have both good computers and operational instruments for characterizing turbulence.

The techniques employed to date by acousticians to characterize turbulence are, for cold jets, the hot-wire method [9, 10], acoustic sensors [11], and, for hot jets, measurement of infrared absorption [15] and laser interferometer photography [16]. Use of the laser velocimeter seems interesting but, to our knowledge, this process has never been applied to characterization of jet

acoustic sources. Moreover, the case of cold jets is the only one which has led to the beginnings of usage in acoustics, by correlation from hot wire and microphone measurements [10, 11, 17, 18]. At the present time, there are no results on usage, in acoustics, of optical measurements in a hot jet. We must agree that this is a task of no small magnitude, adding, to the practical difficulties of developing a method of measuring the significant characteristics of turbulence, those of interpreting and checking the results obtained at each calculation phase, with the delicate problem of the choice of essential approximations to reduce the complexity of the measurement procedure, and computer time.

The above-mentioned difficulties explain the preliminary nature of the results set out below.

## II. THEORETICAL BASES OF THE METHOD EMPLOYED

### II-1. General Equations

The local equations representing flow are the mass conservation equation and the quantity of motion equation; leaving out injection of material and walls, these are written.

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0 \quad (1)$$

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \vec{\nabla} \cdot (\rho \vec{v} \vec{v} - \vec{\sigma}) = 0 \quad (2)$$

where  $\frac{t}{v}$  : time,  $\rho$  : volume mass,  $v$  = fluid velocity;  $\vec{\sigma}$  is the stress tensor, given by the expression:  $\vec{\sigma} = -p \vec{I} + \vec{\tau}$

where  $p$  is the pressure,  $\vec{I}$  the unit tensor  $\vec{\tau}$  the viscous stress tensor.

From equations (1) and (2), Lighthill deduces a relation which is a propagation equation non-homogenous in form, with a

second member interpreted as an acoustic source function:

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = \nabla \nabla \cdot \vec{T} \quad (3)$$

where

$$\square \rho = \nabla \nabla \cdot \vec{T}$$

$c_0$  is the velocity of sound in the medium wherein the observation is made.

$\vec{T}$  is sometimes called Lighthill's tensor, and is equal to

$$\vec{T} = \rho \vec{v} \vec{v} - \vec{\tau} + (p - c_0^2 \rho) \vec{I} \quad (4)$$

The source function  $\nabla \nabla \cdot \vec{T}$  is a scalar quantity, the sum of 3 the terms in the form  $\partial^2 T_{ij} / \partial y_i \partial y_j$  where  $T_{ij} = \rho v_i v_j - \tau_{ij} + (p - c_0^2 \rho) \delta_{ij}$

with  $\delta_{ij} = 1$  if  $i = j$  and  $\delta_{ij} = 0$  if  $i \neq j$  and where the coordinate is relative to the source point.

Outside from turbulent flow, the second member of (3) is negligible, and this equation becomes reduced to the classical sound propagation equation:

$$\square \rho = 0$$

The expression for the far sound field is obtained by integrating (3) and using Kirchoff's theory or a more general method based on double application of Ostrogradski's formula (19). This expression is simplified in the far field, and if the source dimensions are small compared with distance at the observation point of the vector radius  $\vec{x}$ :

$$\rho(\vec{x}, t) = \sum_{ij} \frac{x_i x_j}{4\pi c_0^4 x^3} \int_{V(y)} \left[ \frac{\partial^2 T_{ij}}{\partial t^2} \right]_t d\vec{y} \quad (5)$$

where  $\rho(\vec{x}, t)$  is the perturbation of density due to acoustic waves. In this expression, the differential term between square brackets

is expressed in delayed time  $\hat{t} = t - \frac{|\vec{x} - \vec{y}|}{C_0}$ . This transformation causes the tensorial nature of the source to reappear; to each index component  $i$  and  $j$  is associated the product  $x_i x_j$ .

Bearing in mind the relation  $p = C_0^2 \rho$ , always applicable outside the flow, the acoustic pressure  $p$  at the observation point is written:

$$p(\vec{x}, t) = \sum_{ij} \frac{x_i x_j}{4\pi C_0^2 x^3} \int_{V(y)} \left[ \frac{\partial^2 T_{ij}}{\partial t^2} \right]_{\hat{t}} d\vec{y} \quad (6)$$

and its autocorrelation function is:

$$P(\vec{x}, \tau) = \langle p(\vec{x}, t) \cdot p(\vec{x}, t + \tau) \rangle$$

namely, introducing the expression of the source function:

$$P(\vec{x}, \tau) = \sum_{ijkl} \frac{x_i x_j x_k x_l}{16\pi^2 C_0^4 x^6} \int_{V(\vec{y})} d\vec{y}' \int_{V(\vec{y}'')} d\vec{y}'' \quad (7)$$

$$\left\langle \left[ \frac{\partial^2 T_{ij}}{\partial t^2} \right]_{\hat{t}} \cdot \left[ \frac{\partial^2 T_{kl}}{\partial t^2} \right]_{\hat{t}'' + \tau} \right\rangle$$

where

$$\begin{aligned} T_{ij} &= T_{ij}(\vec{y}, t) \\ T_{kl} &= T_{kl}(\vec{y}'', t) \\ \hat{t} &= t - \frac{|\vec{x} - \vec{y}|}{C_0} \\ \hat{t}'' &= t - \frac{|\vec{x} - \vec{y}''|}{C_0} \end{aligned}$$

Provided conditions are stationary,  $P(\vec{x}, \tau)$  is written in the form:

$$P(\vec{x}, \tau) = \sum_{ijkl} \frac{x_i x_j x_k x_l}{16\pi^2 C_0^4 x^6} \int_{V(\vec{y})} d\vec{y} \int_{V(\vec{\xi})} d\vec{\xi} \quad (8)$$

$$\left[ \frac{\partial^4}{\partial t^4} \left\{ R_{ijkl}(\tau; \vec{y}, \vec{\xi}) \right\} \right]_{\tau = t + t''}$$

with

$$\begin{aligned} \tau &= \hat{t}'' - \hat{t} \\ \vec{\xi} &= \vec{y}'' - \vec{y} \\ \vec{y} &= \frac{1}{2}(\vec{y}' + \vec{y}'') \end{aligned}$$

where we have written:

$$R_{ijkl}(\tau, \vec{y}, \vec{\xi}) = \langle T_{ij}(\vec{y}, t) \cdot T_{kl}(\vec{y}', t + \tau) \rangle \quad (9)$$

This quantity depends only on the source; we will say that  $R_{ijkl}$  is a component of the source correlation tensor  $\vec{R}$ .

Under these conditions, the sound intensity at the observation point, which is equal to:

$$I(\vec{x}) = \frac{\langle p^2(\vec{x}, t) \rangle}{\rho_0 c_0} = \frac{P(\vec{x}, 0)}{\rho_0 c_0}$$

is written:

$$I(\vec{x}) = \sum_{i,j,k,l} \frac{x_i x_j x_k x_l}{16 \pi^2 \rho_0 c_0^5 x^6} \int_{V(\vec{y})} d\vec{y} \int_{V(\vec{\xi})} d\vec{\xi} \left[ \frac{\partial^4}{\partial t'^4} \{ R_{ijkl}(\tau; \vec{y}, \vec{\xi}) \} \right]_{\tau' = \tau''} \quad (10)$$

The acoustical power radiated by the jet, by solid angle unit parallel to the vector radius  $\vec{x}$  is deduced directly from the preceding formula by multiplying by  $x^2$ .

Finally, the spectral density of noise at the observation point  $I(\vec{x}, \omega)$  is the cosine Fourier transform of the autocorrelation function  $P(\vec{x}, \tau)$ :

$$I(\vec{x}, \omega) = \frac{2}{\pi \rho_0 c_0} \int_0^\infty P(\vec{x}, \tau) \cos \omega \tau d\tau$$

where

$$I(\vec{x}, \omega) = \frac{2}{16 \pi^2 \rho_0 c_0^5 x^6} \sum_{i,j,k,l} x_i x_j x_k x_l \int_{V(\vec{y})} d\vec{y} \int_{V(\vec{\xi})} d\vec{\xi} \int_0^\infty \frac{\partial^4}{\partial \tau'^4} \{ R_{ijkl}(\tau; \vec{y}, \vec{\xi}) \} \cos \omega \tau d\tau \quad (11)$$

$\tau' = \tau + \tau''$

It thus appears that, when we know the correlation tensor  $\vec{R}(\tau; \vec{y}, \vec{\xi})$  of the source, we can approach the acoustic parameters we are looking for.

## II-2. Choice of Approximations

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The tensor nature of  $R$  complicates measurement and computer programming in an equally inextricable manner: this is why we are endeavoring to arrive at a solution using a scalar  $R$  function.

In the particular case of cold jets, the isentropic hypothesis  $dp = C_0^2 d\rho$  is applicable to the whole fluid (with the same  $C_0$  value). Moreover, the Reynolds number has a high value, which allows us to neglect the viscous stress tensor vis-a-vis the Reynolds tensor. These considerations lead us to retain a source term in the form  $\frac{\partial^2(\rho v_i v_j)}{\partial y_i \partial y_j}$ . Proudman's analysis [8] of the

expression for pressure at the observation point shows that, in this case, with a suitable choice of coordinate axes, a single tensor term is involved:

$$p(\vec{r}, t) = \frac{1}{4\pi c_0^2 r} \int_{V(\vec{r}, t)} \left[ \frac{\partial^2 (\rho v_x^2)}{\partial t^2} \right]_{\hat{e}} d\vec{y} \quad (12)$$

$v_x$  is the projection of velocity in the direction of the observation point. We can see that, in this case and for a given direction of observation, we can define and measure a scalar function for source correlation.

The restriction involved in the prior choice of the observation direction has been removed by Ribner [5] who shows that, as long as the flow is almost incompressible (subsonic case), the quadripolar distribution  $\rho v_i v_j$  can be replaced by a point source distribution of equal intensity  $\frac{\partial p^{(0)}}{\partial t}$ ,  $p^{(0)}$  being the local density fluctuation created in the turbulent fluid assumed to be isentropic by the local pressure fluctuation due to inertial forces (pseudo-sound). The source term then takes the form  $[\partial^2 p^{(0)} / \partial t^2]$  and the tensor  $\vec{R}$  is replaced by a scalar term  $R$ .

Strictly speaking, in the present status of theory, we are unable to adopt such an approach in the case of hot jets, even in the subsonic range. In the mixing zone, elementary volumes with different densities and temperatures occur in succession at each radius vector point  $\vec{y}$  and, if we accept that, at a first approximation, we have  $dp/dt = 0$ , we must write  $\partial \rho / \partial t = | \vec{v} \cdot \vec{\nabla} \rho \neq 0$ , which prevents us from considering  $\frac{\partial^2 (\rho v_i v_j)}{\partial y_i \partial y_j}$  and  $\vec{\nabla}^2 p^{(0)}$  as equal, according to Ribner's approach. It is therefore no longer possible to assimilate the source to the density fluctuation due to pseudo-sound.

However, for practical reasons, we attempted, in the present exploratory stage, to use scalar R function. Examination of the modifications made to Lighthill's tensor expression by temperature fluctuations shows that the Reynolds tensor terms, and thus the velocity turbulence no longer have the preponderant part to play for hot jets that they do for cold jets, which means that, for a good part of the field that concerns us, the entropy turbulence is an important factor in noise generation.

To support this remark, we may cite an observation of Ribner; when the jet consists of hot air flowing in the outside air, the density reduction due to the rise in temperature (by comparison with the cold jet) produced no measurable effect on the total noise power; according to this author, the turbulent carrying of heat engenders an additional noise, the source of which is the entropy turbulence, which compensates for the noise reduction connected with the density reduction [52].

It is thus interesting to seek to define the R function from a parameter strongly connected with entropy.

### III. PRECISE DEFINITION OF EXPERIMENTATION

The chief target of the experiments consists of verifying whether a scalar function  $R(\tau, \vec{y}, \vec{z})$ , calculated in the first stage after measuring a parameter linked to the jet's entropy, enables us to find out, by a calculation based on the formulation of Section II, the experimental results furnished by direct measurement of the acoustic parameters.

As well as this objective, such a study has a number of practical intentions:

a) Local analysis of hot jet turbulence characteristics for better knowledge of the aerodynamic properties of these jets.

b) Physical research for noise sources of a jet and their 5 location in various regions (mixing zone, developed turbulence) by studying the correlations between the sound picked up by a microphone and a local parameter appropriately chosen in the jet.

c) Refinement and comparison of the various measuring methods applicable to hot jet turbulence.

In the present stage of development of this technique by O.N.E.R.A. and SNECMA, the standard experiment has the following phases:

1. Setting up study models in the anechoic chamber of the Engine Testing Center at Saclay (Fig. 1).

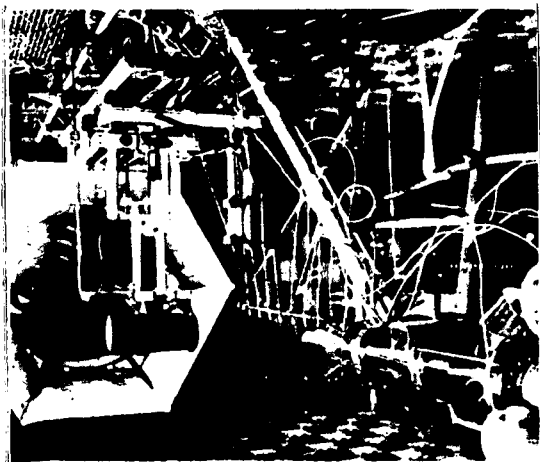


Fig. 1. Anechoic Chamber, Saclay



2. Characterization of turbulence by the optical method, described below in Section IV.

3. Picking up significant acoustic quantities by a microphone located in the far field and mounted on a revolving arm, and microphones placed along a line parallel to the jet axis.

4. Processing of data from optical and acoustic receivers, by correlation methods.

5. Computer calculation of acoustic quantities starting from turbulence characteristics (See Section V).

6. Comparison between the variations in these quantities, for different turbulence parameter values, and those of the acoustic quantities measured.

Preparatory experiments (setting up optical measuring and turbulence characterization equipment, without acoustic measurements were carried out in a specially equipped cell at the O.N.E.R.A. laboratories.

#### IV. TURBULENCE CHARACTERIZATION METHOD

##### IV-1. Selection of Physical Parameter Measured

As shown above, we chose a simple parameter to be measured and explained, whose relationship to isentropy, even if it is difficult to explain, comes out of physical reasoning. This parameter is the infrared brightness of the jet. It is clear that we will have some difficulty in estimating, starting from the fluctuations in this parameter, the absolute values of local turbulence intensity and the corresponding source term. On the other hand, all these space-time quantities significant for defining the source term, such as the length of the correlation, the speed of convections, the lifetime of the vortices, can be measured with sufficient accuracy if we simply assume that the infrared brightness is closely connected with entropy in the entire volume examined [20].

In the following paragraph we will see how this partial characterization of turbulence is worked out in the present phase of the study.

#### IV-2. Method of Measurement

The method adopted, inspired by Schetter [15] consists of gathering, from a receiver with suitable optical devices, the infrared radiation from a small volume of the turbulent medium studied. The arrangement is shown in figure 2 below. Two receivers

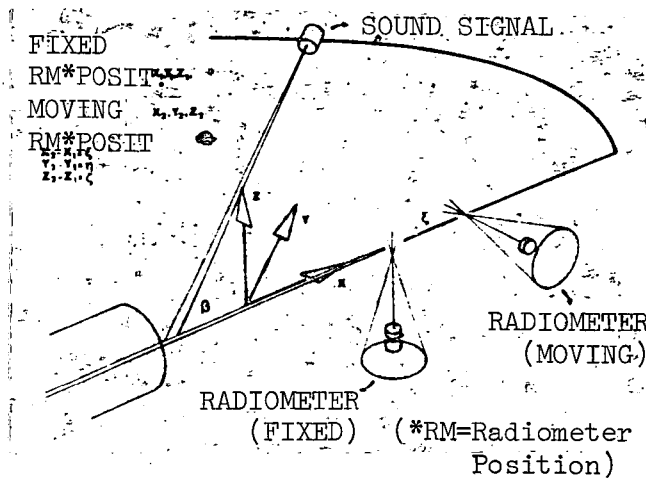


Fig. 2. System Diagram

with optical axes perpendicular to each other and orthogonal to the axis of the jet are used. Each receiver simultaneously analyses the infrared emission from all points of the jet located in the vicinity of the optical /6 axis; however it was possible to give these radiometers some spatial definition along this axis by arranging a dia-

phragm along the optical path playing the part of a pupil. This gives high weight to the infrared emission of the volume located in the position conjugate to that of the diaphragm. If we wish to improve spatial definition still further, it is necessary to use two pieces of apparatus with optical axes intersecting at a point still to be determined, and to use a method of correlation. This configuration in particular permits the autocorrelation coefficient  $C(\vec{y}, 0, \tau)$  of the infrared emission of the point in question to be defined. Finally, if both axes are shifted from the distance  $\xi$ , we measure the cross-correlation coefficient  $C(\vec{y}, \xi, \tau)$ . Plotting the curves of  $C$  as a function of  $\tau$  for different values of  $\xi$  we can show up the space-time parameters of turbulence (see Section VII).



This type of measurement demands a carefully-designed vibrationproof mechanical assembly, permitting controlled and accurate movement of the optical axis of at least one radiometer while the acoustic experiment is proceeding.

#### IV-3. Description of Apparatus

The equipment is capable of analyzing a zone with diameter 4 mm inside a jet of between 700 K and 1100 K in temperature, in the presence of substantial interference light due to hot gases and the heating (to red) of the nozzle. It is insensitive to the high-level sound and vibration perturbations. The region of the spectrum selected (1 to 3  $\mu$ m) allows us to work on the water vapor emission bands.

Figure 3 shows one of the radiometers used for this purpose. It is a very compact instrument, with two simultaneous measuring



Fig. 3. A Radiometer.

channels. It is composed of a Cassegrain telescope and two receiving cells. One modulated channel measures the continuous or very low frequency components of the signal and a second broadband channel measures the fast

fluctuations connected with turbulence. The optical paths of the two channels are doubled with the aid of a separating laser in the immediate vicinity of the cells. The modulated channel receives only 10% of the total flux.

The cells used are of the lead sulfide type and need no cooling. However, they must be sorted to select the best. Their internal resistance is high (500 K  $\Omega$ ) and utilization of impedance adaptation electronics, with a frequency correction network, permits

a flat passband at approximately 1 dB to be obtained up to 20 kHz. We should finally point out that the system dynamics were designed with particular care, since the measurements to be made cover a large range of generating temperatures and expansion rates. Saturation occurs only above about one hundred volts output voltage, while the electronic noise itself has an effective value of about 1 mV.

## V. METHOD OF UTILIZING THE EXPERIMENTAL RESULTS

Calculation of the acoustic parameters demands that we know the function R at any point of flow. In theory, this function is a tensor calculated from the terms  $T_{ij}$ , but this method is impracticable since it is impossible to measure these terms directly, and there are experimental and mathematical difficulties caused by the choice of a high resolution. This is why the method of utilization selected is based on the following simplifying hypotheses:

a) The scalar function R is assumed to have an analytic form independent of  $\vec{y}$  inside one and the same zone of the jet.

The flow is divided for this purpose into a small number of zones A, B, .... N, etc.

b) The function R is assumed to be Gaussian, in the form:

$$R(\tau, \vec{y}, \vec{r}) = R_N \exp \left\{ -\frac{(\tau_1 - U_{CN} \tau)^2}{L_{1N}^2} - \frac{\tau_2^2}{L_{2N}^2} - \frac{\tau_3^2}{L_{3N}^2} - \frac{\tau^2}{\tau_N^2} \right\}$$

with:

$R_N$  = turbulence intensity in zone N

$U_{CN}$  = convection velocity in zone N

$L_{1N}$  = correlation length along the axis of the jet in zone N

$L_{2N}, L_{3N}$  = correlation length perpendicular to the axis of the jet in the zone N

$\tau_N$  = duration of vortices in the zone N.

The choice of a Gaussian function is based /7  
on the indications given by various authors [5, 8]. It makes  
calculation easier and is theoretically substantiated only for  
homogenous turbulence. Thereafter, other types of functions can  
be tried.

c) The quantities  $U_{CN}$ ,  $L_{10}$ ,  $\epsilon_N$  are supplied by infrared  
experimentation.

d) The quantity  $R_N$  is estimated very roughly from infra-  
red experimentation. In the present state of technology, the dif-  
ficulties inherent in accurate evaluation of  $R_N$  still prevent the  
method from giving results with absolute values: at present we  
can only predict that the variations in the acoustic parameters  
as a function of the turbulence characteristics.

Using the above hypotheses, two working series can be develo-  
ped from the method:

1. It is possible, in a preliminary stage, to calculate,  
by digital computer experiments, the variations in the acoustical  
quantities as a function of characteristics (selected arbitrarily)  
of turbulence. The existence of a large number of input parameters  
and the difficulty of, a priori, predicting the evolution of the

final results, demands a dia-  
log with the computer. This  
is why these digital experi-  
ments were done using the  
IBM 22-50 display console  
connected to the 360-50 com-  
puter and the O.N.E.R.A. Com-  
puter Center. It is thus pos-  
sible to display the final  
calculated result in real time  
on a large cathode screen and



Fig. 4. IBM 2250 Display Console

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to superimpose the curves representing several successive calculations and so compare them (Figure 4).

Figure 5 shows a representative sample of the sound intensity  $I(\theta, M_c)$  calculation results as a function of the angle of observation  $\theta$  for various values of the convection Mach number  $M_c$  [21].

2. The digital experiment permits guidance in the choice of  $L_1, L_2$  parameters which infrared measurement does not supply.

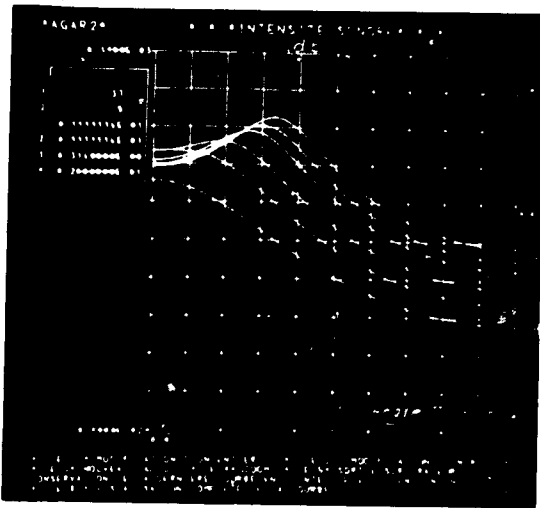


Fig. 5. Variations in sound intensity as a function of the angle of observation for different values of the convection Mach number  $M_c$ .

It is then possible to utilize the computer to calculate all acoustic quantities as a function of the measured turbulence characteristics, it being understood that certain secondary quantities, not measured, must be chosen empirically.

We thus obtain the sound intensity, the spectrums, and the PNdB for various angular positions.

## VI. METHOD OF ACQUIRING AND PROCESSING THE DATA

### VI-1. Intensity of Turbulence

At the present state of technology, the intensity of turbulence in a zone N is estimated roughly from a single radiometer, obtaining the quotient of the fluctuation signal (video channel) by the continuous signal (modulated channel).

## VI-2. Space-Time Parameters

Utilization of two radiometers permits us to arrive at  $U_{c,n}$  and  $\mathcal{L}_{c,n}, \mathcal{E}_n$  by measuring infrared-infrared correlations. We will not describe the elementary transformations for obtaining these values, since they are classic (see Section VII).

From a radiometer plus a microphone, we can measure the infra- /8 red-sound correlations and deduce the contribution of the various parts of the jet to the sound intensity at the microphone. Calculation of cross spectrum densities permits the sources of the various parts of the spectrum to be assigned sound intensity at the various flow regions.

## VI-3. Brief Description of Equipment Used

During the preparatory experiments in a cell installed in the O.N.E.R.A. laboratories, analog tape-recording and hybrid processing in real time of the infrared-infrared correlations was adopted: this technique permits selection of significant recordings (which were digitalized), space-time coefficients, and turbulence intensities. Calculations were then performed on an IBM 360-50 computer.

During the experiments in an anechoic chamber, use in real time of the Engine Testing Center IBM 1800 computer permitted valuable time to be saved. Acquisition was accomplished by an analog-digital converter (for quantities permitting calculation of the turbulence intensity) and a Newlett-Packard correlator (for space-time quantities). After calibration, the results of this operation were recorded on numeric magnetic tape and transmitted by for calculation of the acoustic quantities to the O.N.E.R.A. Computer Center.

In a later phase, we will do the major part of the preliminary or auxiliary calculations (cross spectrum densities) on



Figure 6. O.N.E.R.A./Chatillon automatic noise measurement analysis laboratory.

equipment set up at O.N.E.R.A. under the auspices of STAE, which has the Spectral Dynamics analysers and a CII 10.020 computer facilitating data management and transmission to the IBM 360-50 computer.

Figure 6 is a view of this facility currently being prepared for operation.

## VII. SOME PRELIMINARY RESULTS

### VII-2. Turbulence Intensity

A radiometer placed at various distances from the nozzle output plane moves radially. Each of the two measuring channels fur-

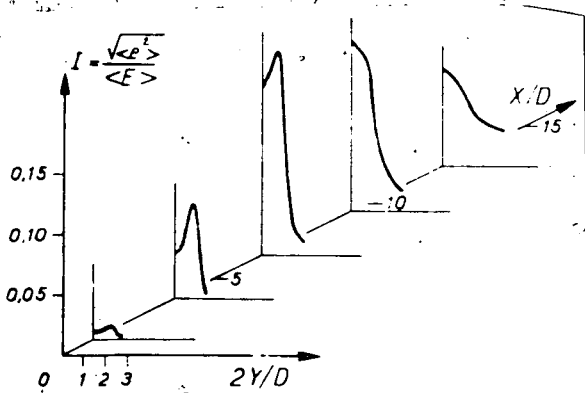


Fig. 7. Three-dimensional representation of transversal profiles measured with a radiometer at various distances  $X/D$  from the plane of the nozzle output.

nishes, respectively, the square root of the root mean square  $(\langle e^2 \rangle)^{1/2}$  and the mean signal value  $\langle E \rangle$ . Evolution of the  $(\langle e^2 \rangle)^{1/2} / \langle E \rangle$  ratio (Figure 7) reflects the geometry of the mixing zone. This ratio, linked to the turbulence intensity, is at a maximum at the end of the potential cone, which shows up the importance of this zone for sound emission.

### VII-2. Space-Time Parameters

Correlation coefficients  $C_{12}(\xi, \tau)$  are calculated from measurements and we deduced, by elementary calculations, the

characteristic quantities for turbulence. We should recall that index 1 marks radiometer 1, and index 2, radiometer 2:  $\xi$  is equal to the distance between the axes carrying radiometers 1 and 2 (Figure 2) and  $\tau$  represents the lag.

Figure 8 shows an axial profile example of the convection speed  $U_c = \xi/\tau_M$  where  $\tau_M$  is the abscissa of the maximum of the curve  $C_{12}(\xi, \tau)$ . We note that this velocity goes through a maximum around the end of the potential cone.

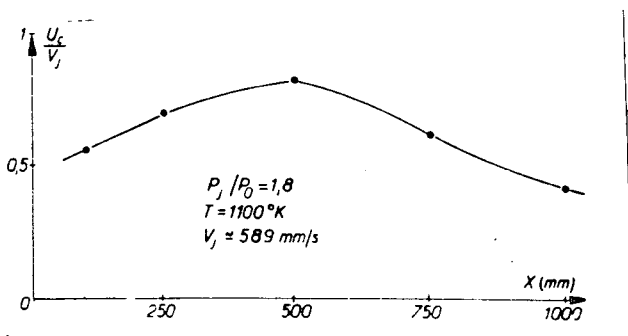


Fig. 8. Axial profile of the convection velocity.

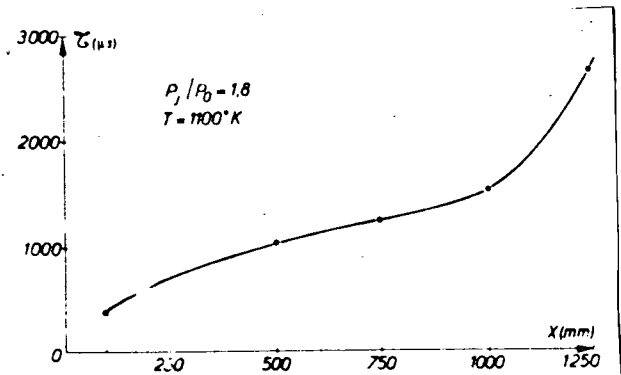


Fig. 9. Axial profile of the integrated scale of lifetime.

Figure 9 shows an example of the axial profile of the integral scale of lifetime  $Z_1 = \int_0^\infty C_{12}(\xi, \tau_M) d\tau_M$ , where  $C_{12}(\xi, \tau_M)$  is the ordinate of the maximum of  $C_{12}(\xi, \tau)$ . /9

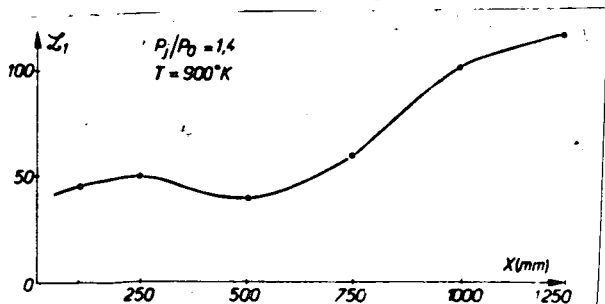


Fig. 10. Axial profile of the integral scale of the axial correlation length

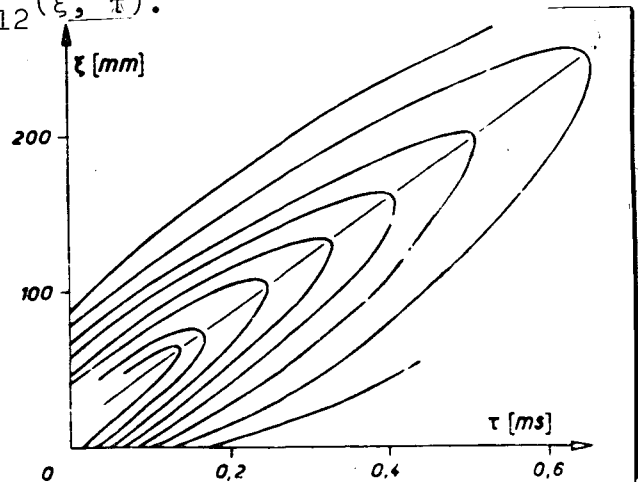


Fig. 11. Isocorrelations  $X/D = 7.8$   
 $M_j = 0.97$   $T_j = 900$  K

Figure 10 gives an example of the axial profile of the integral scale of the axial correlation length.

Figure 11 shows an example of isocorrelations taken at about 8 diameters.

The spectrum densities of the electric signals coming from the radiometers permit us to study the evolution of the spectrum. On Figure 12a the spectrum intensity of the infrared signal is presented. The radiometer is placed 25 cm from the nozzle plane.

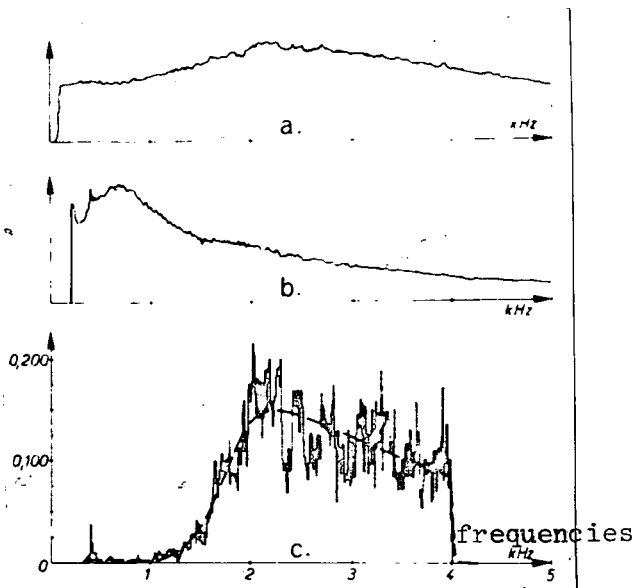


Fig. 12. Infrared-sound cross spectra.

a) spectrum densities (arbitrary units) for infrared signal  $R = 0$   $X = 25$  cm.

b) spectrum densities (arbitrary units) of microphone signal  $R = 35$  cm  $X = 150$  cm

c) square of coherence coefficient in frequency band 0.2 - 4 kHz.

We observe a clear spectrum peak at  $f \approx 2.3$  kHz. Figure 12b shows the spectrum of a microphone signal picked up at 150 cm from the nozzle output plane and 35 cm from the jet axis; this spectrum peaks at  $f \approx 0.8$  kHz.

Figure 12c represents the square of the coherence coefficient\* of these two signals in the frequency band 0.2 to 4 kHz. This curve has a maximum on the order of 0.4 (rather high) at  $f \approx 2.3$  kHz.

We can thus study the contribution to sound emission of various volumes of the jet.

\* Definition of coherence coefficient:

$$(\text{Coherence Coef.})^2 = \frac{\text{cross spectrum density}}{(\text{spectrum density})_{\text{microphone}} \times (\text{spectrum density})_{\text{infrared}}}$$

### VII-3. Acoustic Parameters

Starting from space-time quantities and following the procedure discussed in Section V, we calculate the sound intensity and the spectrums for various angular positions. On Figure 13 the calculated sound intensity compared to the measured sound intensity in the anechoic chamber at the Engine Design Center at Saclay.

We observe fairly good agreement in the vicinity of the maximum emission angle, and non-negligible divergence further from

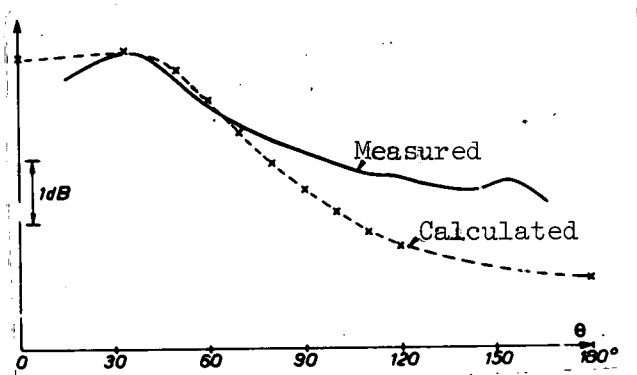


Fig. 13. Comparison of measured sound intensity and calculated sound intensity as a function of  $\theta$  for  $\rho_j/\rho_o=1.8$  and  $T=1,100$  K.  $\theta$  is the angle between the direction of observation and the axis of the jet.

this angle. This disagreement is explained by the approximations introduced in the present stage of these calculations. We expect one improvement when we take into account the effects of refraction. /10

different modes of operation we find

a) that calculation very accurately predicts the direction of variations of all acoustic quantities.

b) that calculation takes into account, with good accuracy, the quantities of relative variations of the following parameters:

- maximum angle of emission
- frequency of the spectrum density curve peak, for the maximum angle of emission
- difference between the maximum and minimum on sound intensity.

## VIII. CONCLUSION

At the present state of experimentation, only a few preliminary results were obtained. Thus far, it has not been possible to give a definitive conclusion as to the validity of this method and the approximations employed. It is however possible to draw some provisional conclusions from the results already acquired:

1) Despite the approximations used, the method permits location of turbulent regions of the jet and rough evaluation of the relative sizes of the various noise sources;

2) The contribution of the various parts of the jet to intensity measured at a point exterior to the flow appears clearly from infrared sound correlations, even if the local jet emission is broadband;

3) The evolution of the acoustic parameters measured in an anechoic chamber by causing the motor parameters to vary, coincide well in direction and approximately in quantity with the variation of the same parameters as calculated, under the same conditions, from the R function defined in Section V and worked out from measurements defined in Section IV.

At a later stage of the study, it would be appropriate to examine the possibilities of using a finer method of characterization using, if necessary, one additional measurement; at any event it appears necessary to go ahead with the theory and physical interpretation of the measurement results on hot jets in order to provide solid foundations for a method which, at present, is still too empirical.

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